Ray Tracing Acceleration

CS 4620 Lecture 22

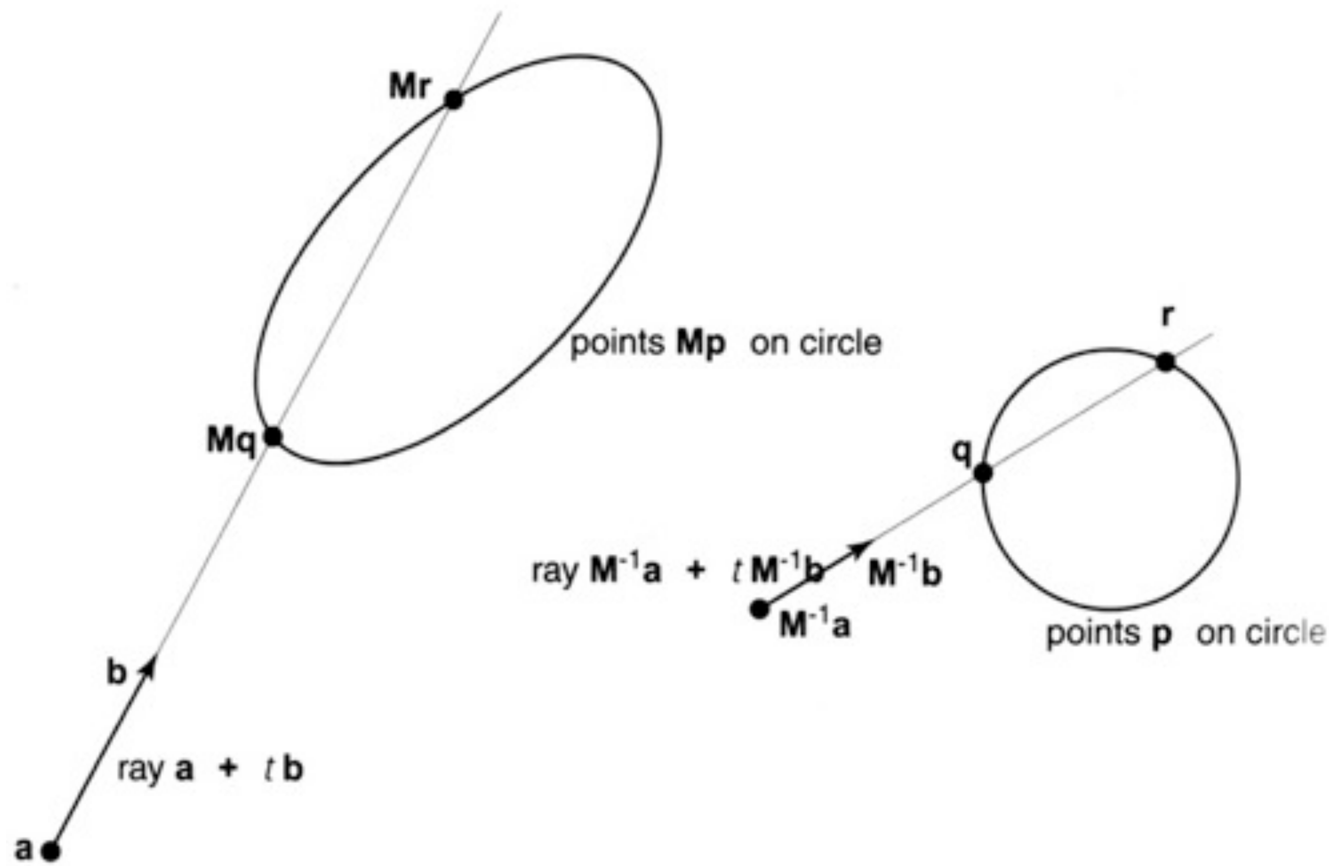
Topics

- Transformations in ray tracing
  - Transforming objects
  - Transformation hierarchies
- Ray tracing acceleration structures
  - Bounding volumes
  - Bounding volume hierarchies
  - Uniform spatial subdivision
  - Adaptive spatial subdivision

Transforming objects

- In modeling, we've seen the usefulness of transformations
  - How to do the same in RT?
- Take spheres as an example: want to support transformed spheres
  - Need a new Surface subclass
- Option 1: transform sphere into world coordinates
  - Write code to intersect arbitrary ellipsoids
- Option 2: transform ray into sphere's coordinates
  - Then just use existing sphere intersection routine

Intersecting transformed objects



[S]

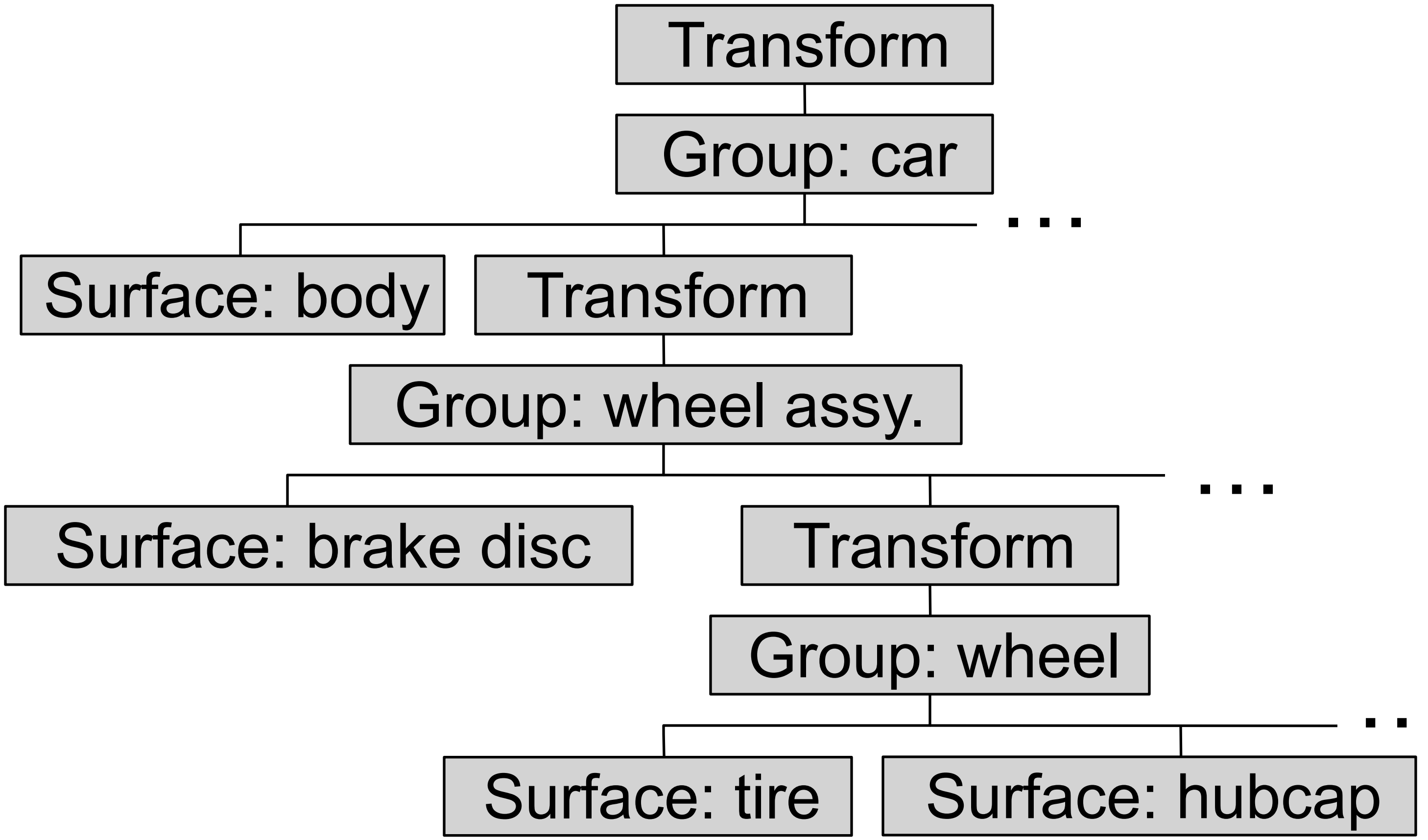
Implementing RT transforms

- Create wrapper object "TrasformedSurface"
  - Has a transform T and a reference to a surface S
  - To intersect:
    - Transform ray to local coords (by inverse of T)
    - Call surface.intersect
    - Transform hit data back to global coords (by T)
      - Intersection point
      - Surface normal
      - Any other relevant data (maybe none)

Groups, transforms, hierarchies

- Often it's useful to transform several objects at once
  - Add "SurfaceGroup" as a subclass of Surface
    - Has a list of surfaces
    - Returns closest intersection
      - Opportunity to move ray intersection code here to avoid duplication
- With TransformedSurface and SurfaceGroup you can put transforms below transforms
  - Voilà! A transformation hierarchy.

A transformation hierarchy

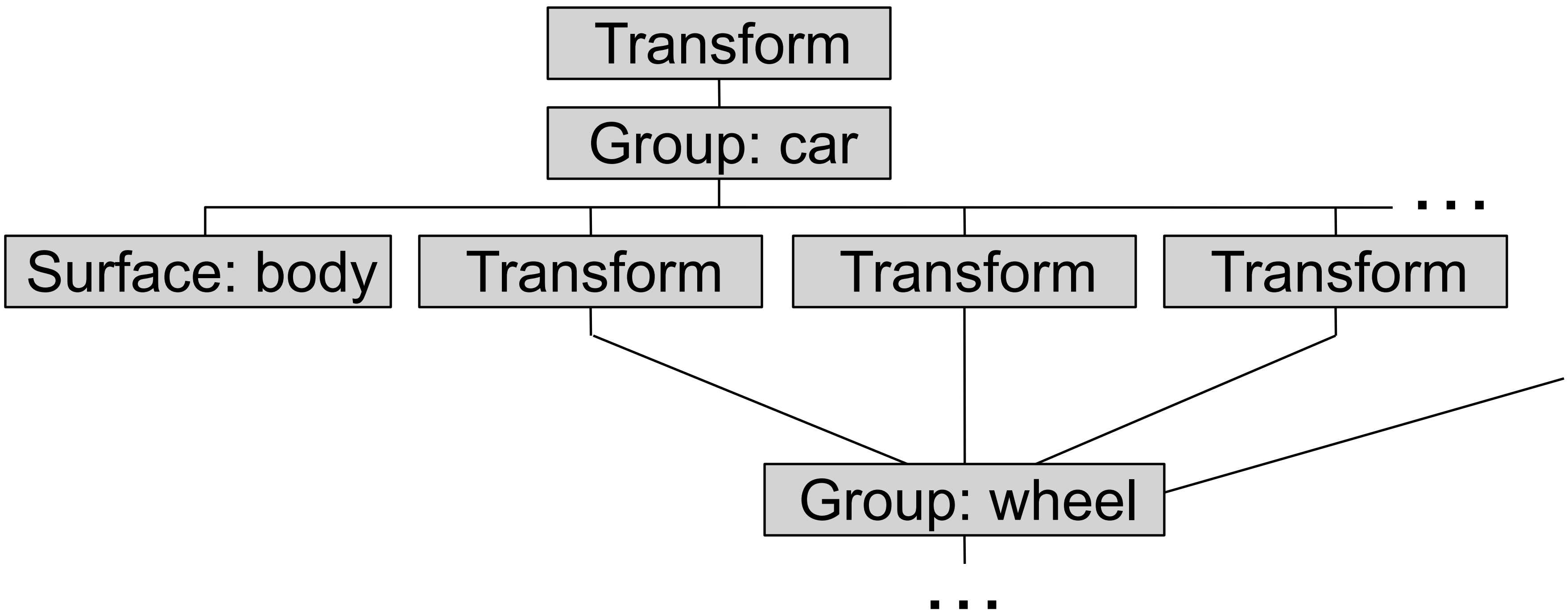


– Common optimization: merge transforms with groups

Instancing

- Anything worth doing is worth doing *n* times
- If we can transform objects, why not transform them several ways?
  - Many models have repeated subassemblies
    - Mechanical parts (wheels of car)
    - Multiple objects (chairs in classroom, …)
  - Nothing stops you from creating two TransformedSurface objects that reference the same Surface
    - Allowing this makes the transformation tree into a DAG
      - (directed acyclic graph)
    - Mostly this is transparent to the renderer

Hierarchy with instancing



Hierarchies and performance

- Transforming rays is expensive
  - minimize tree depth: flatten on input
    - push all transformations toward leaves
    - triangle meshes may do best to stay as group
      - transform ray once, intersect with mesh
  - internal group nodes still required for instancing
    - can't push two transforms down to same child!

TransformGroup {
xf: $\mathbf{A}$
Mesh {
$\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3, \ldots$
}
TransformGroup {
xf: $\mathbf{B}$
Sphere {
radius: r
}
}
}

Mesh {
xf: $\mathbf{A}$
$\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3, \ldots$
}
Sphere {
xf: $\mathbf{BA}$
radius: r
}

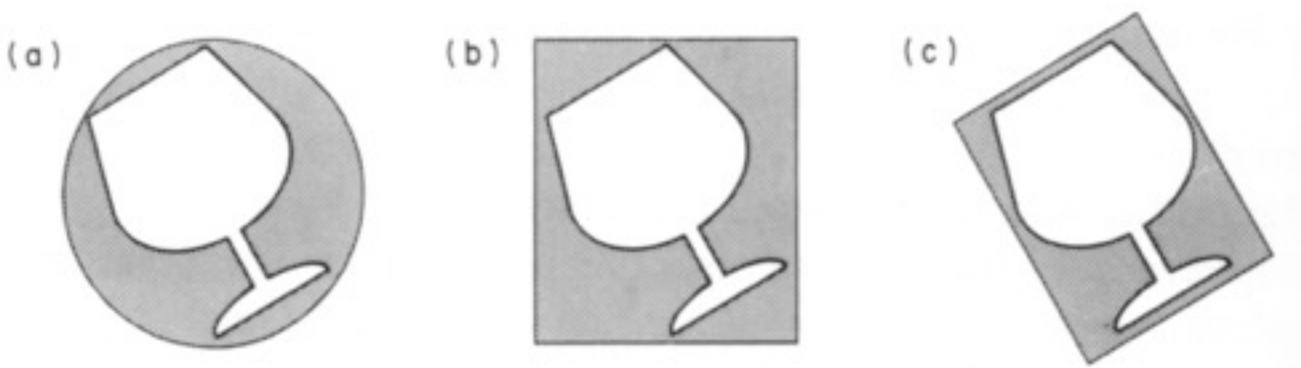
Mesh {
$\mathbf{Av}_1, \mathbf{Av}_2, \mathbf{Av}_3, \ldots$
}
Sphere {
xf: $\mathbf{BA}$
radius: r
}

Ray tracing acceleration

- Ray tracing is slow. This is bad!
  - Ray tracers spend most of their time in ray-surface intersection methods
- Ways to improve speed
  - Make intersection methods more efficient
    - Yes, good idea. But only gets you so far
  - Call intersection methods fewer times
    - Intersecting every ray with every object is wasteful
    - Basic strategy: efficiently find big chunks of geometry that definitely do not intersect a ray

Bounding volumes

- Quick way to avoid intersections: bound object with a simple volume
  - Object is fully contained in the volume
  - If it doesn't hit the volume, it doesn't hit the object
  - So test bvol first, then test object if it hits



[Glassner 89, Fig 4.5]

Bounding volumes

- Cost: more for hits and near misses, less for far misses
- Worth doing? It depends:
  - Cost of bvol intersection test should be small
    - Therefore use simple shapes (spheres, boxes, …)
  - Cost of object intersect test should be large
    - Bvols most useful for complex objects
  - Tightness of fit should be good
    - Loose fit leads to extra object intersections
    - Tradeoff between tightness and bvol intersection cost

Implementing bounding volume

- Just add new Surface subclass, "BoundedSurface"
  - Contains a bounding volume and a reference to a surface
  - Intersection method:
    - Intersect with bvol, return false for miss
    - Return surface.intersect(ray)
  - Like transformations, common to merge with group
  - This change is transparent to the renderer (only it might run faster)
- Note that all Surfaces will need to be able to supply bounding volumes for themselves

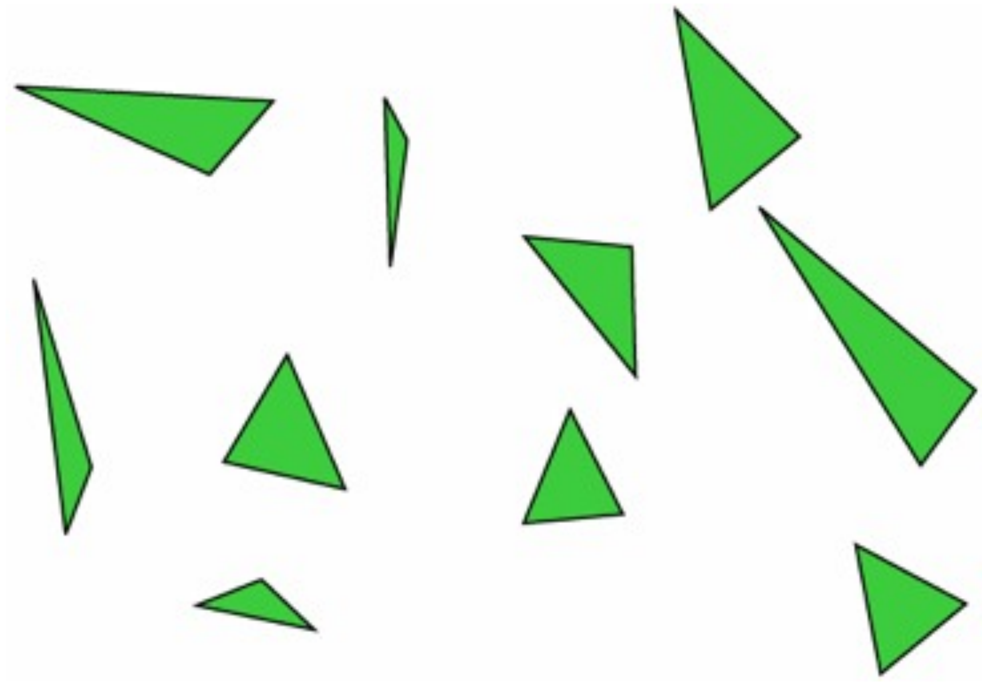
If it's worth doing, it's worth doing hierarchically!

- Bvols around objects may help
- Bvols around groups of objects will help
- Bvols around parts of complex objects will help
- Leads to the idea of using bounding volumes all the way from the whole scene down to groups of a few objects

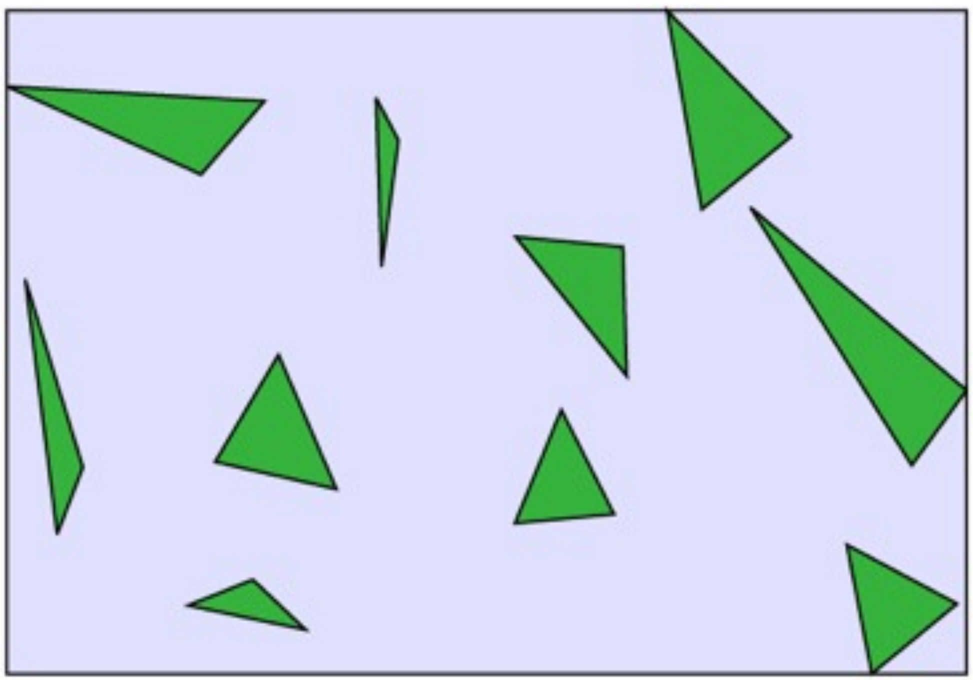
Implementing a bvol hierarchy

- A BoundedSurface can contain a list of Surfaces
- Some of those Surfaces might be more BoundedSurfaces
- Voilà! A bounding volume hierarchy
  – And it’s all still transparent to the renderer

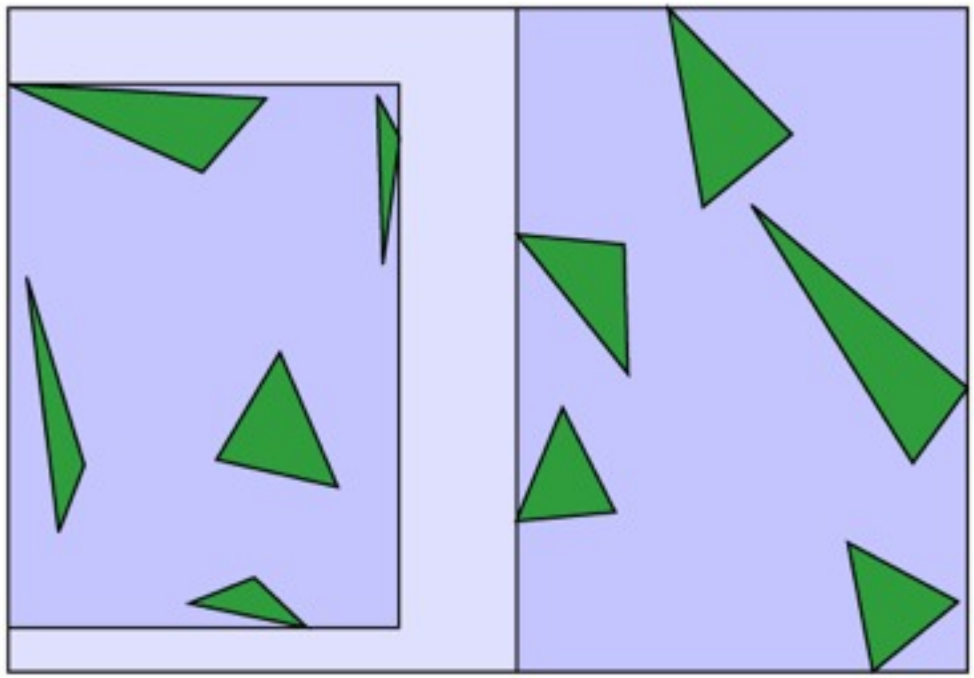
BVH construction example



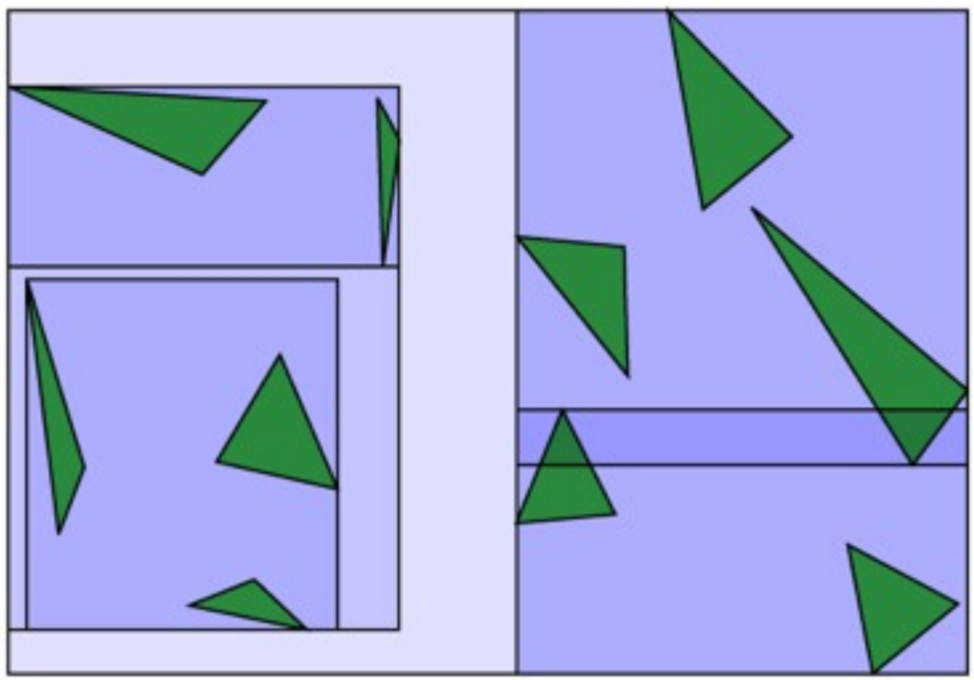
BVH construction example



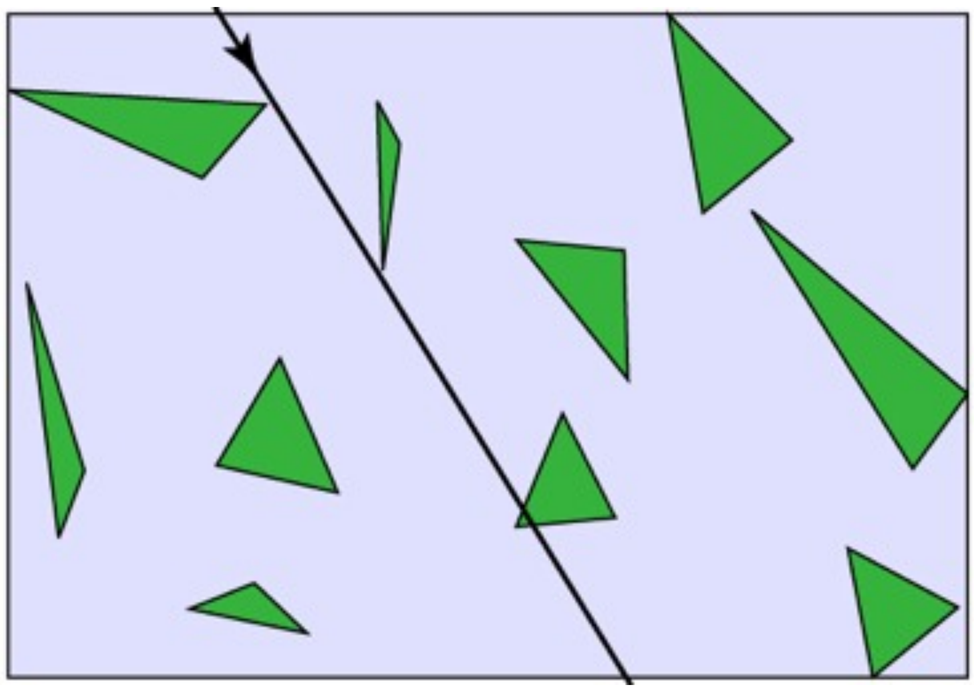
BVH construction example



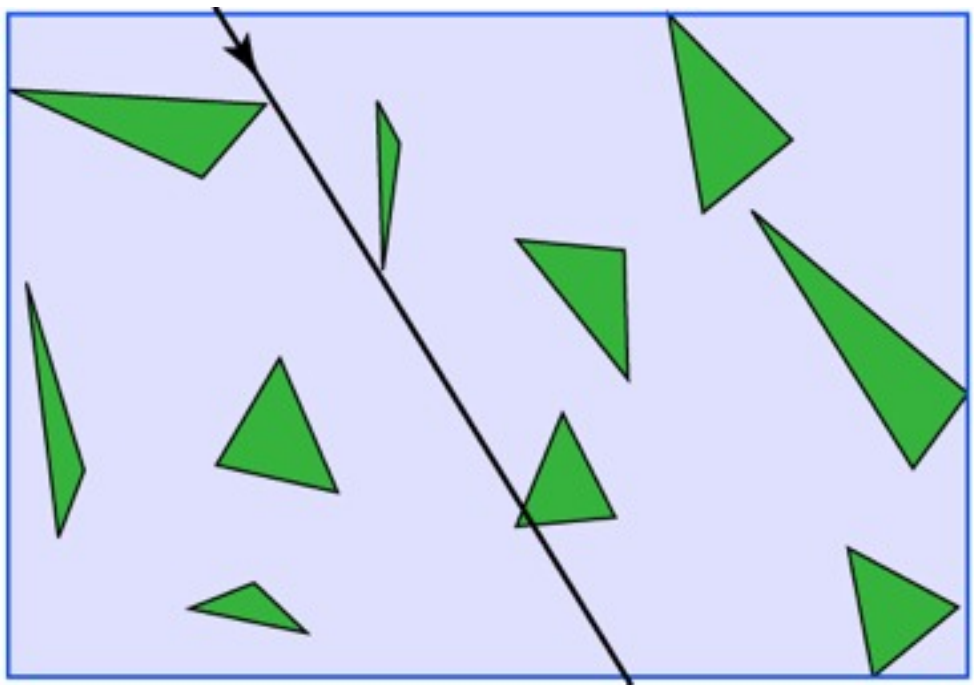
BVH construction example



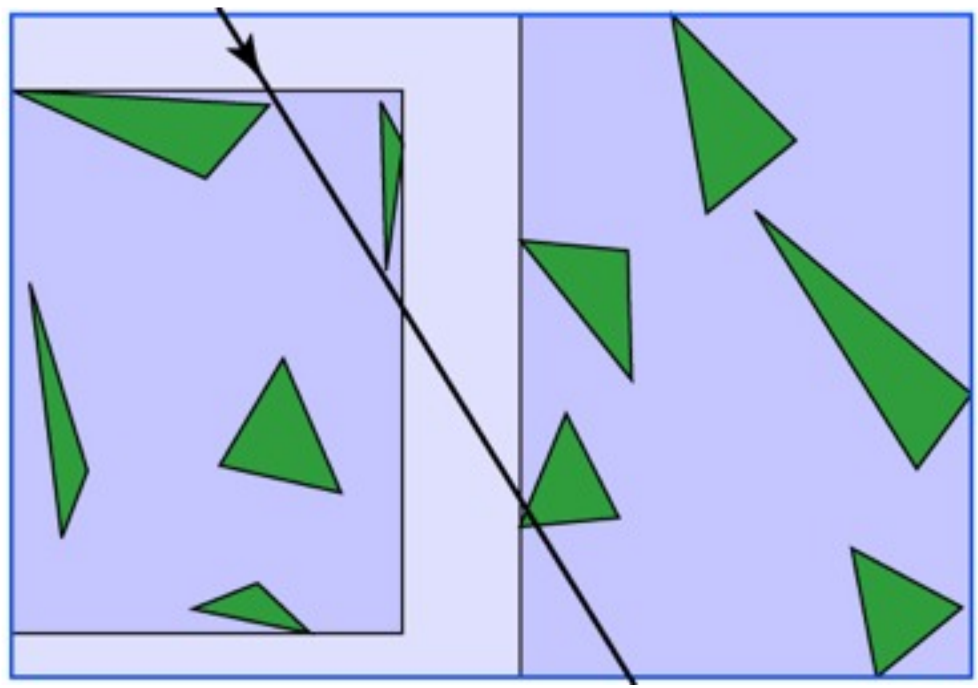
BVH ray-tracing example



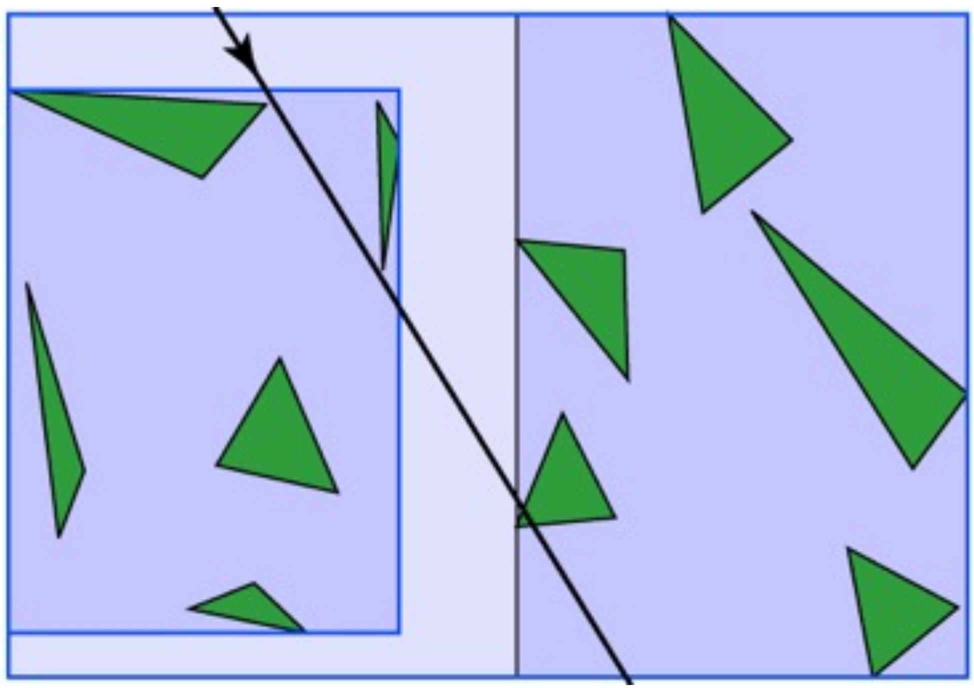
BVH ray-tracing example



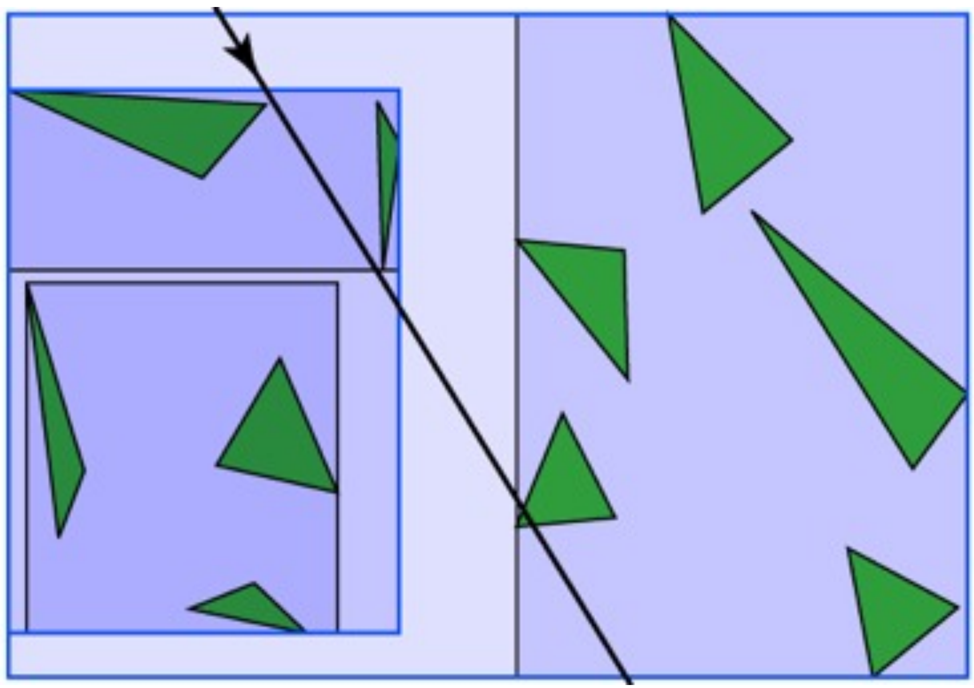
BVH ray-tracing example



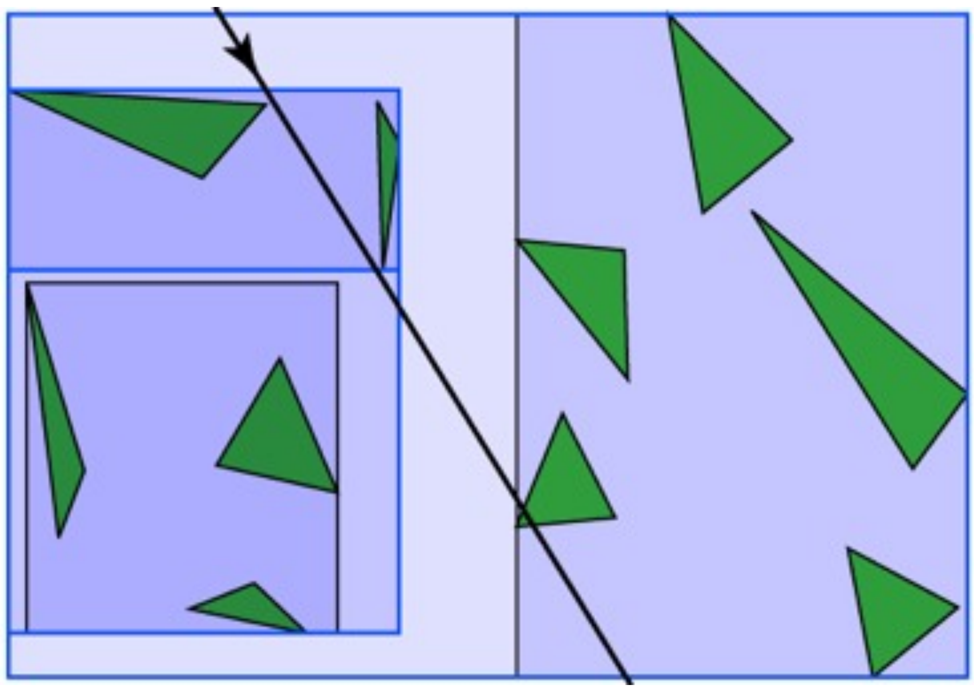
BVH ray-tracing example



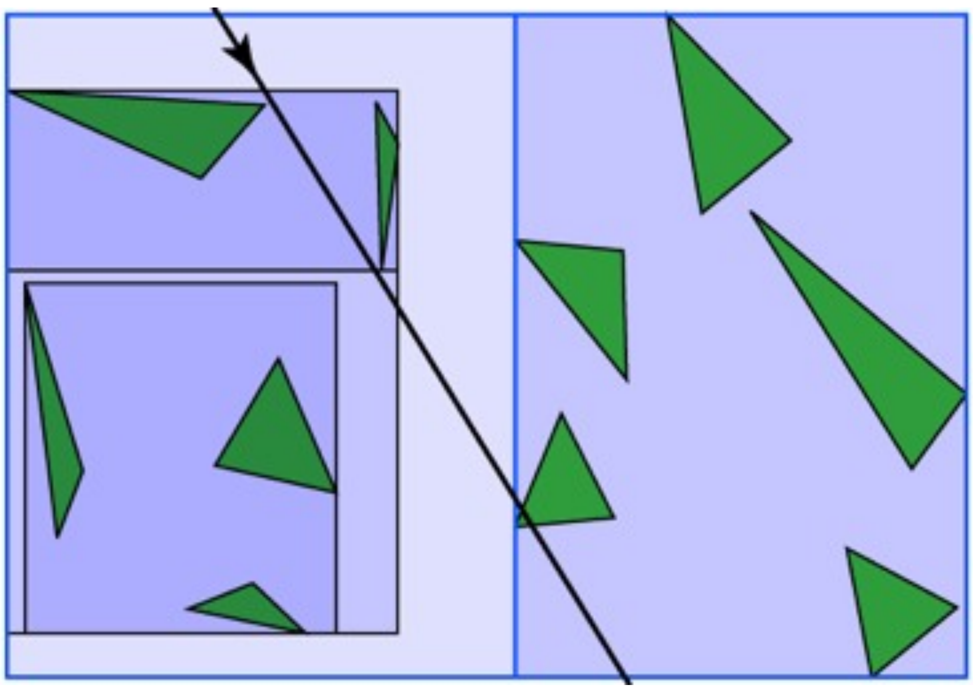
BVH ray-tracing example



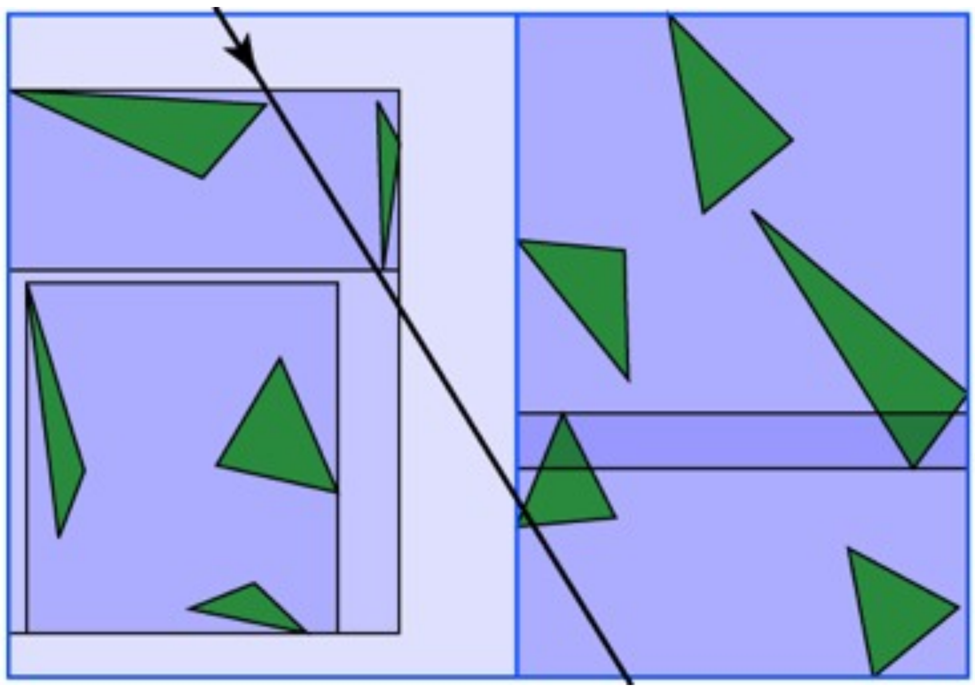
BVH ray-tracing example



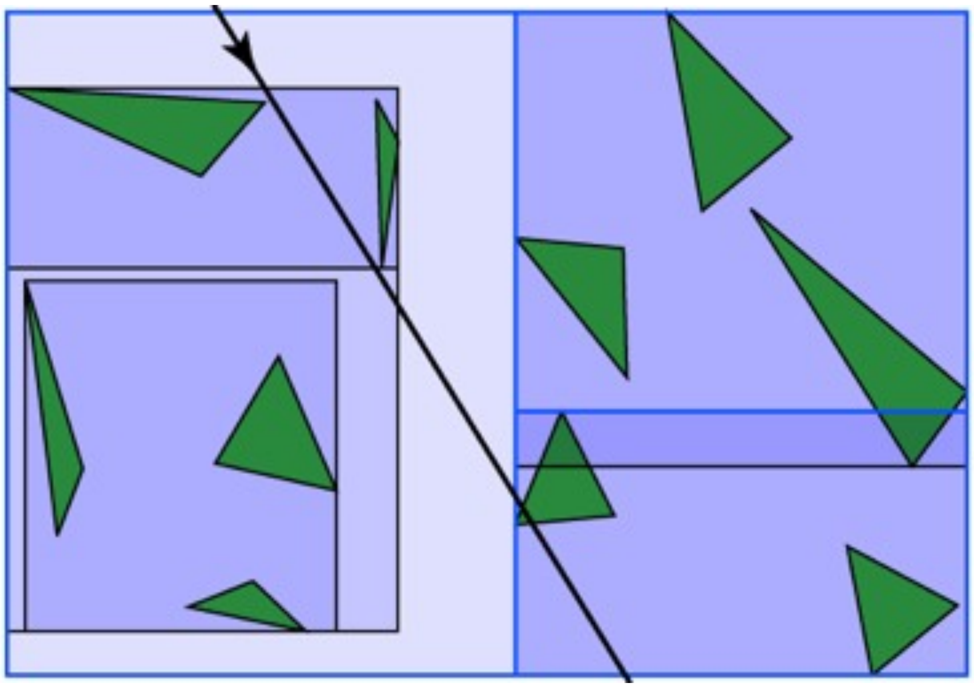
BVH ray-tracing example



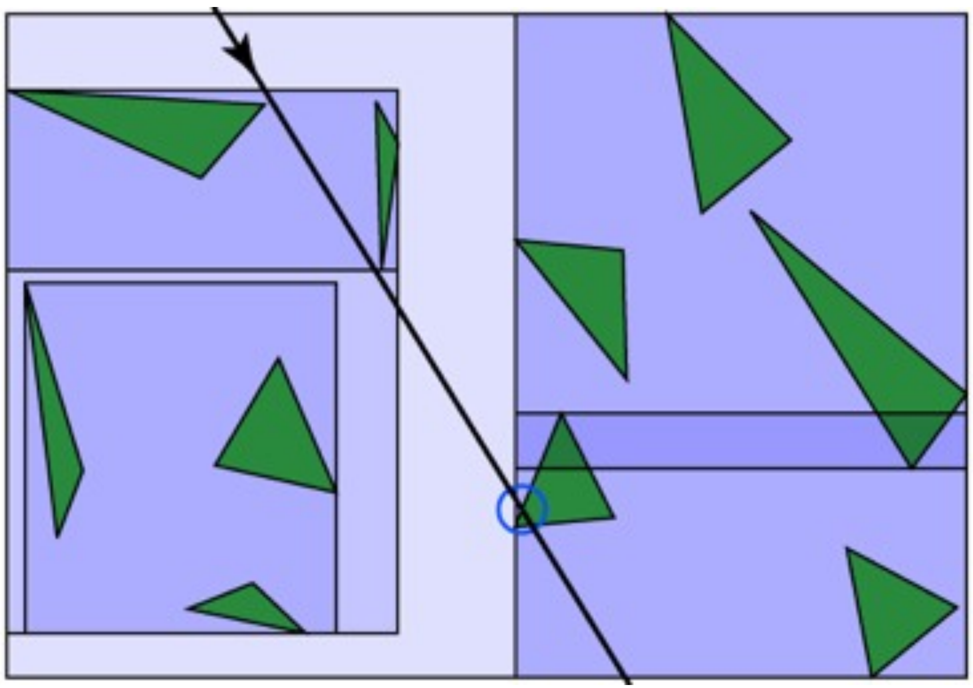
BVH ray-tracing example



BVH ray-tracing example



BVH ray-tracing example



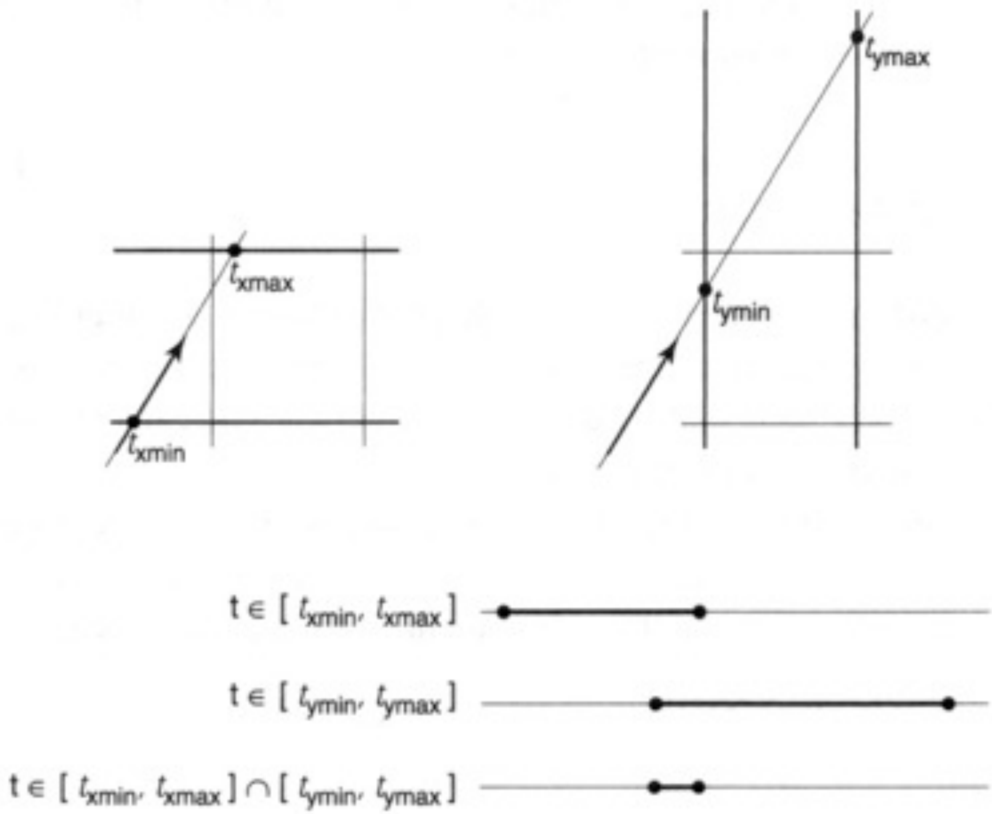
Choice of bounding volumes

- Spheres -- easy to intersect, not always so tight
- Axis-aligned bounding boxes (AABBs) -- easy to intersect, often tighter (esp. for axis-aligned models)
- Oriented bounding boxes (OBBs) -- easy to intersect (but cost of transformation), tighter for arbitrary objects
- Computing the bvols
  - For primitives -- generally pretty easy
  - For groups -- not so easy for OBBs (to do well)
  - For transformed surfaces -- not so easy for spheres

Axis aligned bounding boxes

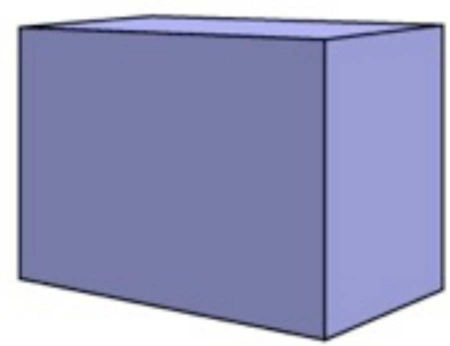
- Probably easiest to implement
- Computing for primitives
  - Cube: duh!
  - Sphere, cylinder, etc.: pretty obvious
  - Groups or meshes: min/max of component parts
- AABBs for transformed surface
  - Easy to do conservatively: bbox of the 8 corners of the bbox of the untransformed surface
- How to intersect them
  - Treat them as an intersection of slabs (see Shirley)

Intersecting boxes



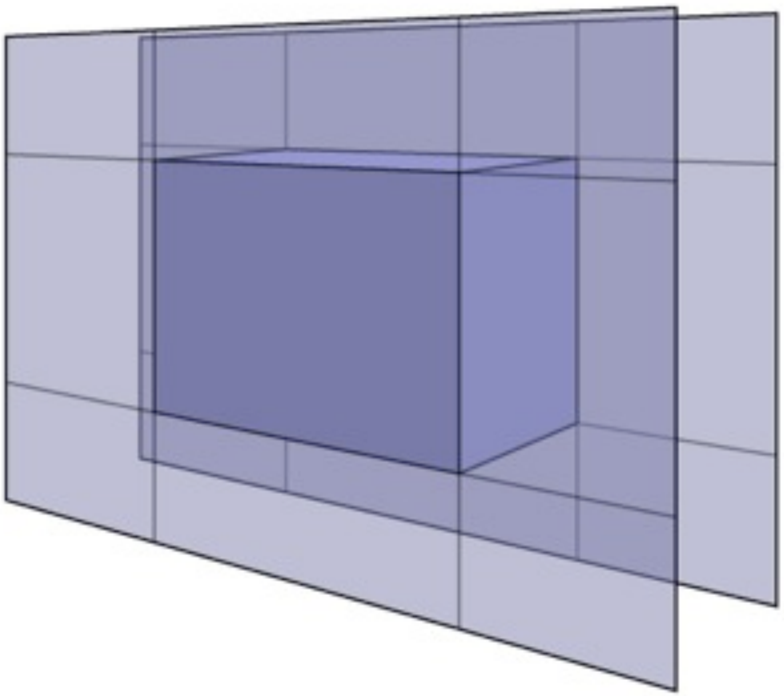
Ray-box intersection

- Could intersect with 6 faces individually
- Better way: box is the intersection of 3 slabs



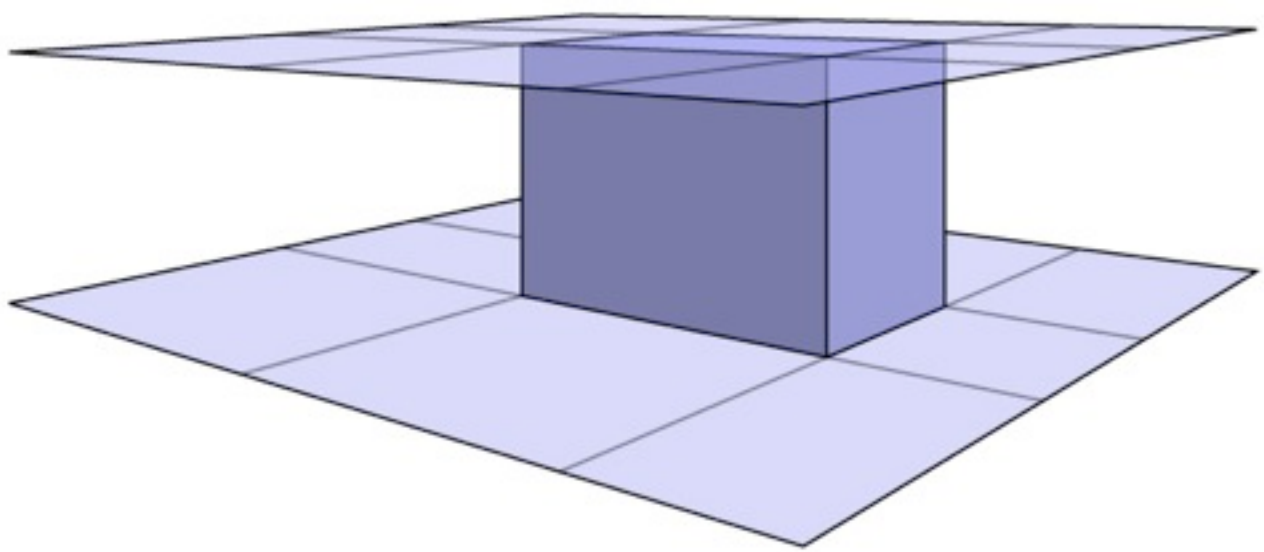
Ray-box intersection

- Could intersect with 6 faces individually
- Better way: box is the intersection of 3 slabs



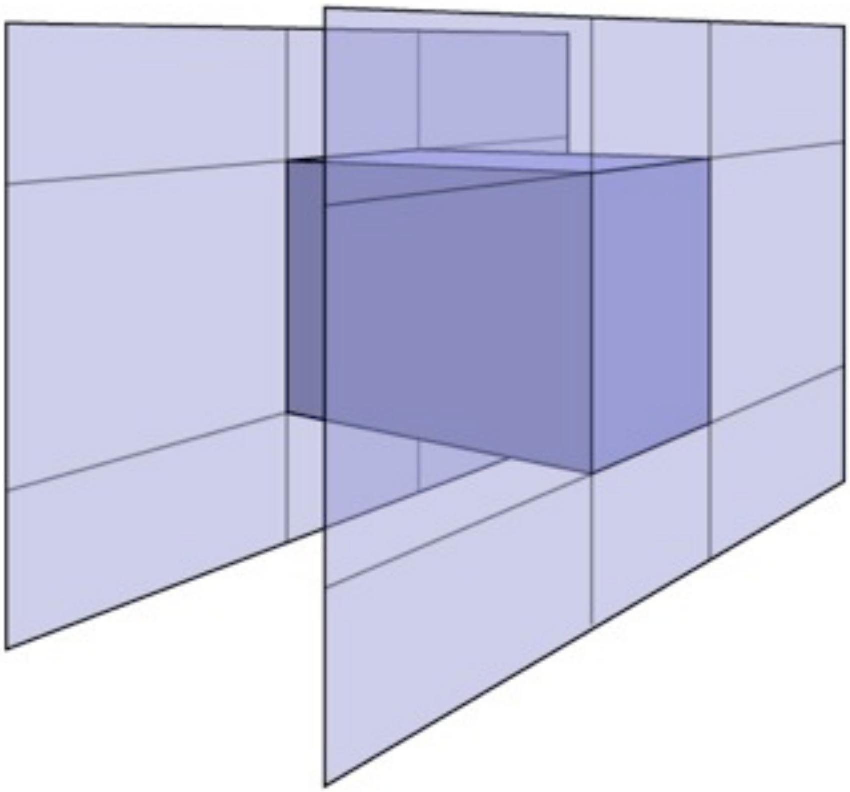
Ray-box intersection

- Could intersect with 6 faces individually
- Better way: box is the intersection of 3 slabs



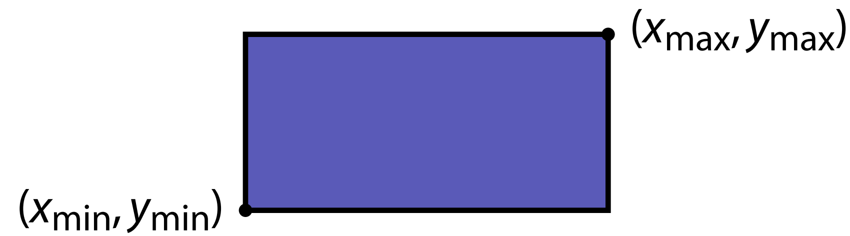
Ray-box intersection

- Could intersect with 6 faces individually
- Better way: box is the intersection of 3 slabs



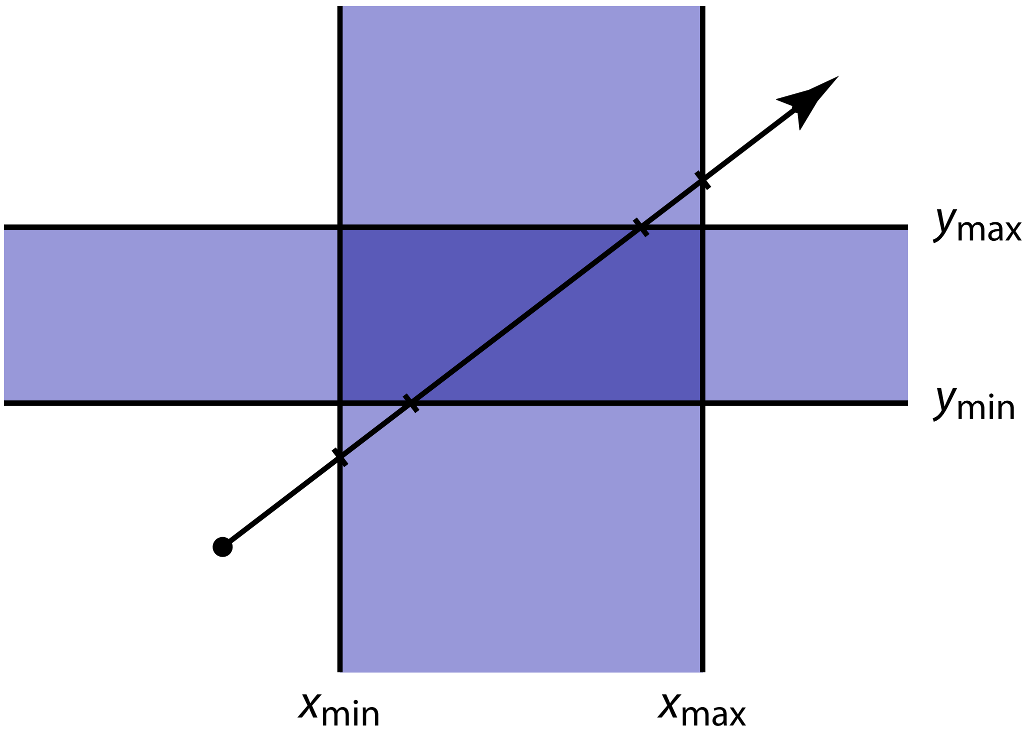
Ray-slab intersection

- 2D example
- 3D is the same!



Ray-slab intersection

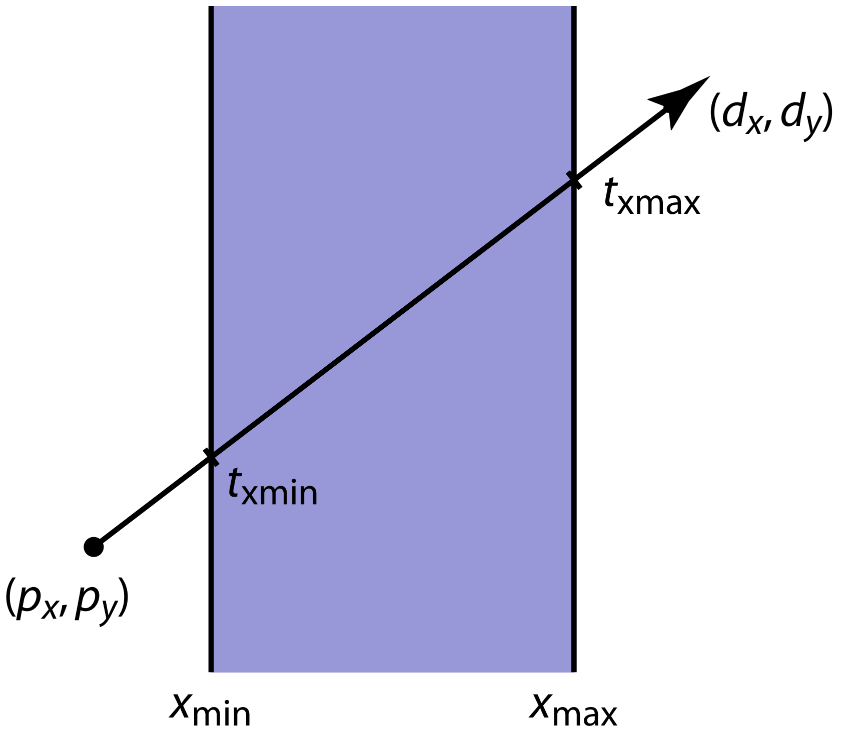
- 2D example
- 3D is the same!



Ray-slab intersection

- 2D example
- 3D is the same!

$$p_x + t_{x\min}\, d_x = x_{\min}$$
$$t_{x\min} = (x_{\min} - p_x)/d_x$$

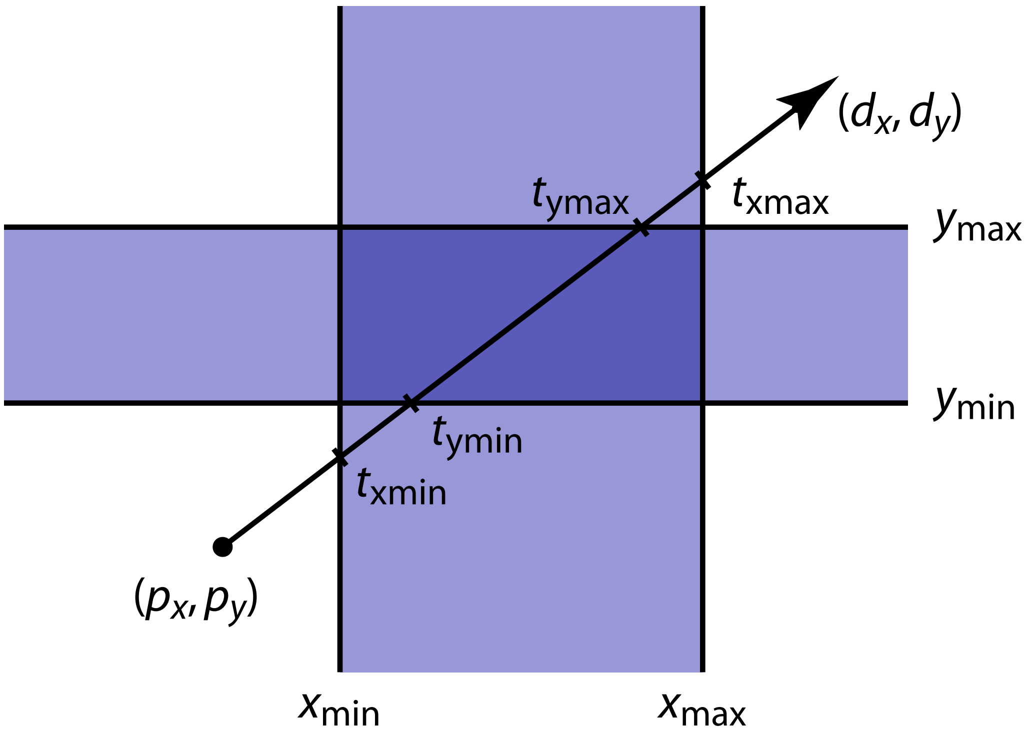


Ray-slab intersection

- 2D example
- 3D is the same!

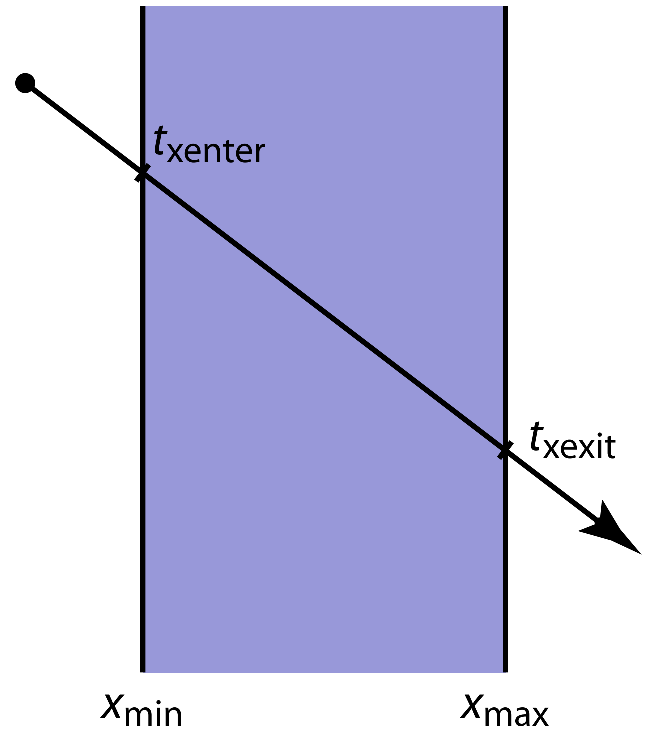
$$p_x + t_{x\min}\, d_x = x_{\min}$$
$$t_{x\min} = (x_{\min} - p_x)/d_x$$

$$p_y + t_{y\min}\, d_y = y_{\min}$$
$$t_{y\min} = (y_{\min} - p_y)/d_y$$



Intersecting intersections

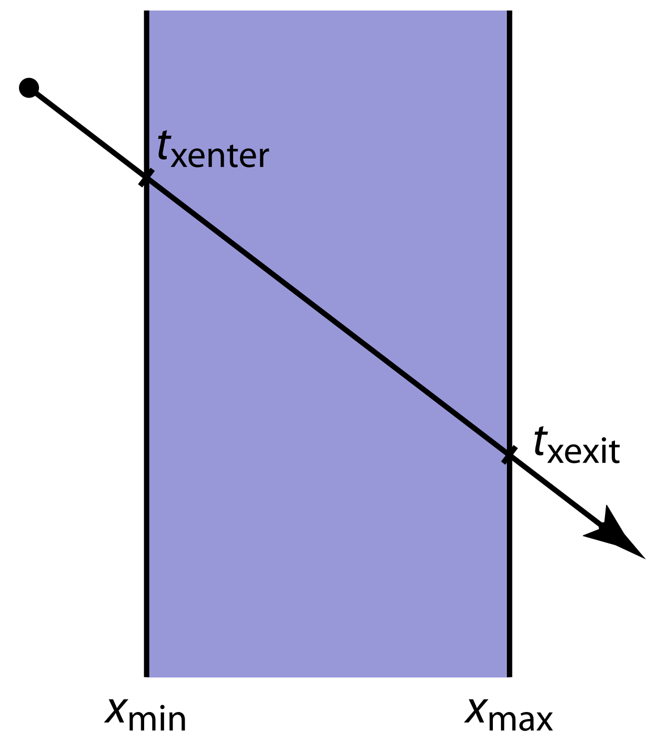
- Each intersection is an interval
- Want last entry point and first exit point



Intersecting intersections

- Each intersection is an interval
- Want last entry point and first exit point

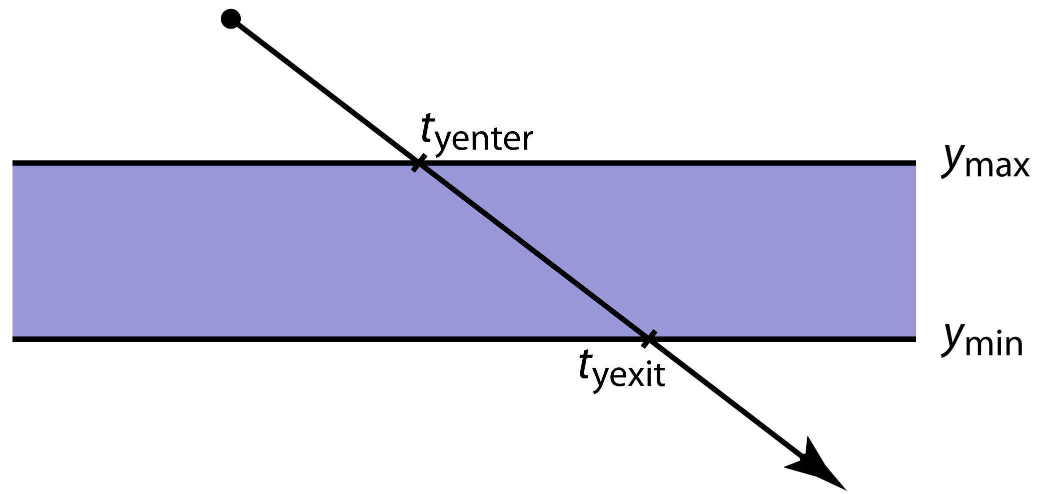
$$t_{x\text{enter}} = \min(t_{x\min}, t_{x\max})$$
$$t_{x\text{exit}} = \max(t_{x\min}, t_{x\max})$$



Intersecting intersections

- Each intersection is an interval
- Want last entry point and first exit point

$$t_{x\text{enter}} = \min(t_{x\min}, t_{x\max})$$
$$t_{x\text{exit}} = \max(t_{x\min}, t_{x\max})$$

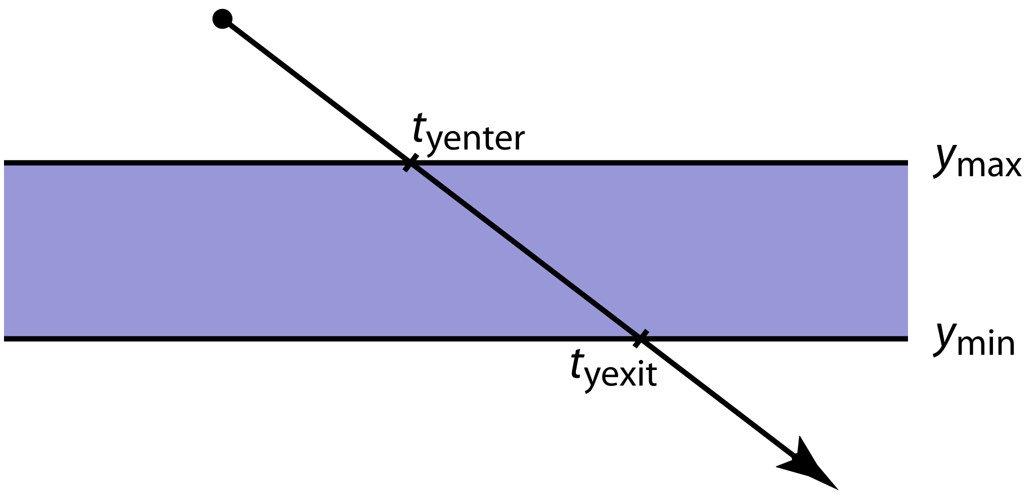


Intersecting intersections

- Each intersection is an interval
- Want last entry point and first exit point

$$t_{x\text{enter}} = \min(t_{x\min}, t_{x\max})$$
$$t_{x\text{exit}} = \max(t_{x\min}, t_{x\max})$$

$$t_{y\text{enter}} = \min(t_{y\min}, t_{y\max})$$
$$t_{y\text{exit}} = \max(t_{y\min}, t_{y\max})$$

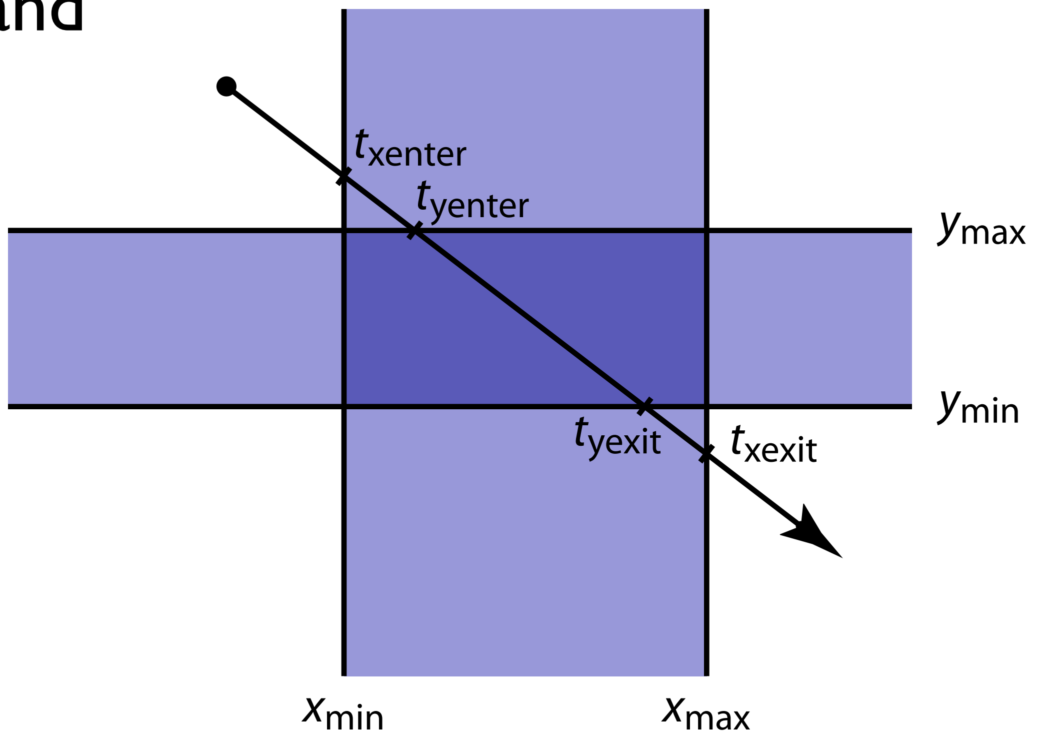


Intersecting intersections

- Each intersection is an interval
- Want last entry point and first exit point

$$t_{x\text{enter}} = \min(t_{x\text{min}}, t_{x\text{max}})$$
$$t_{x\text{exit}} = \max(t_{x\text{min}}, t_{x\text{max}})$$

$$t_{y\text{enter}} = \min(t_{y\text{min}}, t_{y\text{max}})$$
$$t_{y\text{exit}} = \max(t_{y\text{min}}, t_{y\text{max}})$$



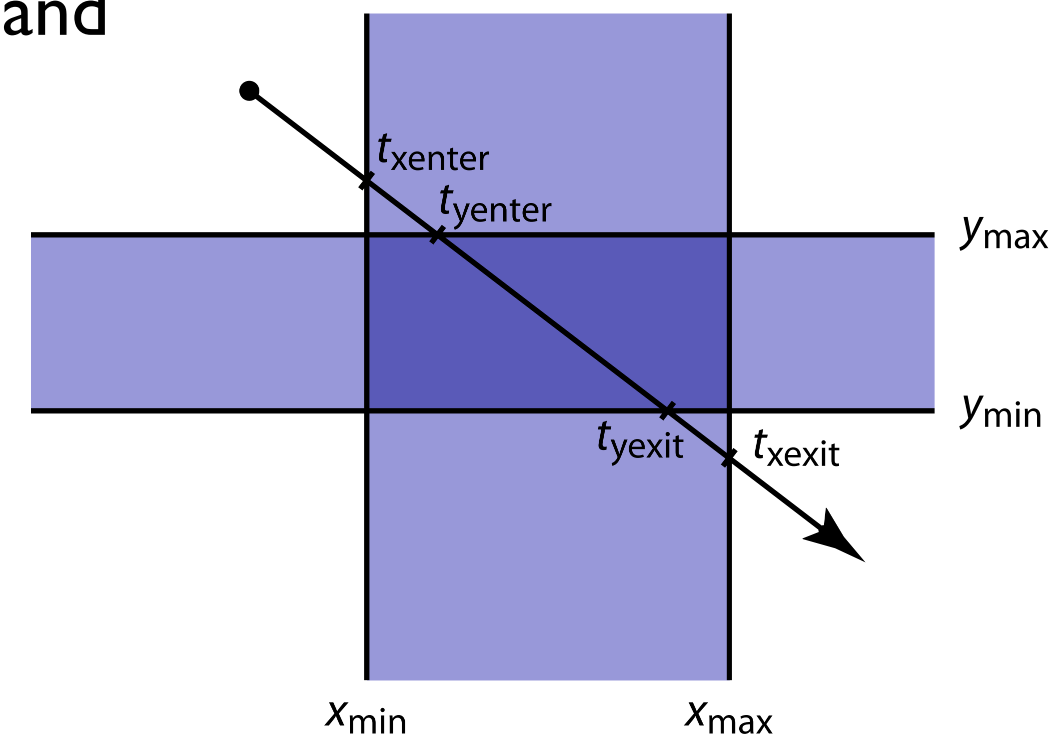
Intersecting intersections

- Each intersection is an interval
- Want last entry point and first exit point

$$t_{x\text{enter}} = \min(t_{x\text{min}}, t_{x\text{max}})$$
$$t_{x\text{exit}} = \max(t_{x\text{min}}, t_{x\text{max}})$$

$$t_{y\text{enter}} = \min(t_{y\text{min}}, t_{y\text{max}})$$
$$t_{y\text{exit}} = \max(t_{y\text{min}}, t_{y\text{max}})$$

$$t_{\text{enter}} = \max(t_{x\text{enter}}, t_{y\text{enter}})$$
$$t_{\text{exit}} = \min(t_{x\text{exit}}, t_{y\text{exit}})$$



Building a hierarchy

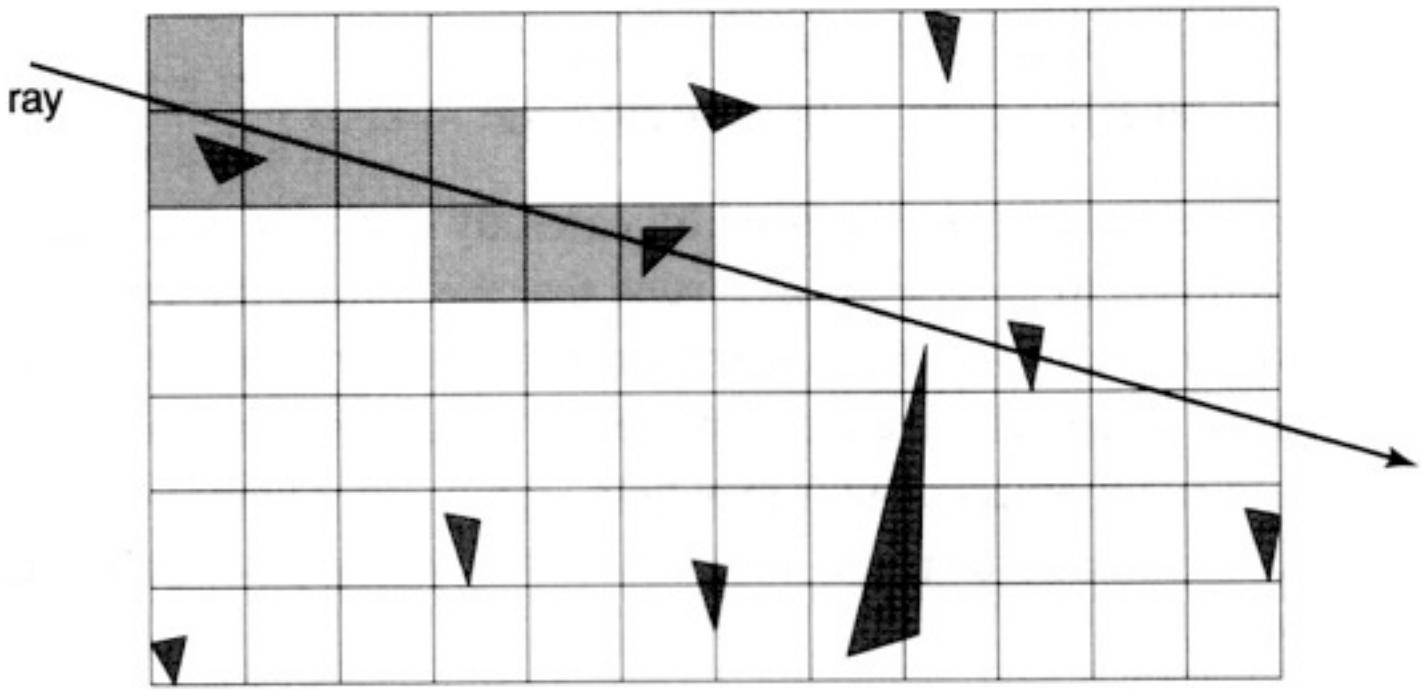
- Usually do it top-down
- Make bbox for whole scene, then split into (maybe 2) parts
  - Recurse on parts
  - Stop when there are just a few objects in your box

Building a hierarchy

- How to partition?
  - Ideal: clusters
  - Practical: partition along axis
    - Center partition
      - Less expensive, simpler
      - Unbalanced tree (but may sometimes be better)
    - Median partition
      - More expensive
      - More balanced tree
    - Surface area heuristic
      - Model expected cost of ray intersection
      - Generally produces best-performing trees

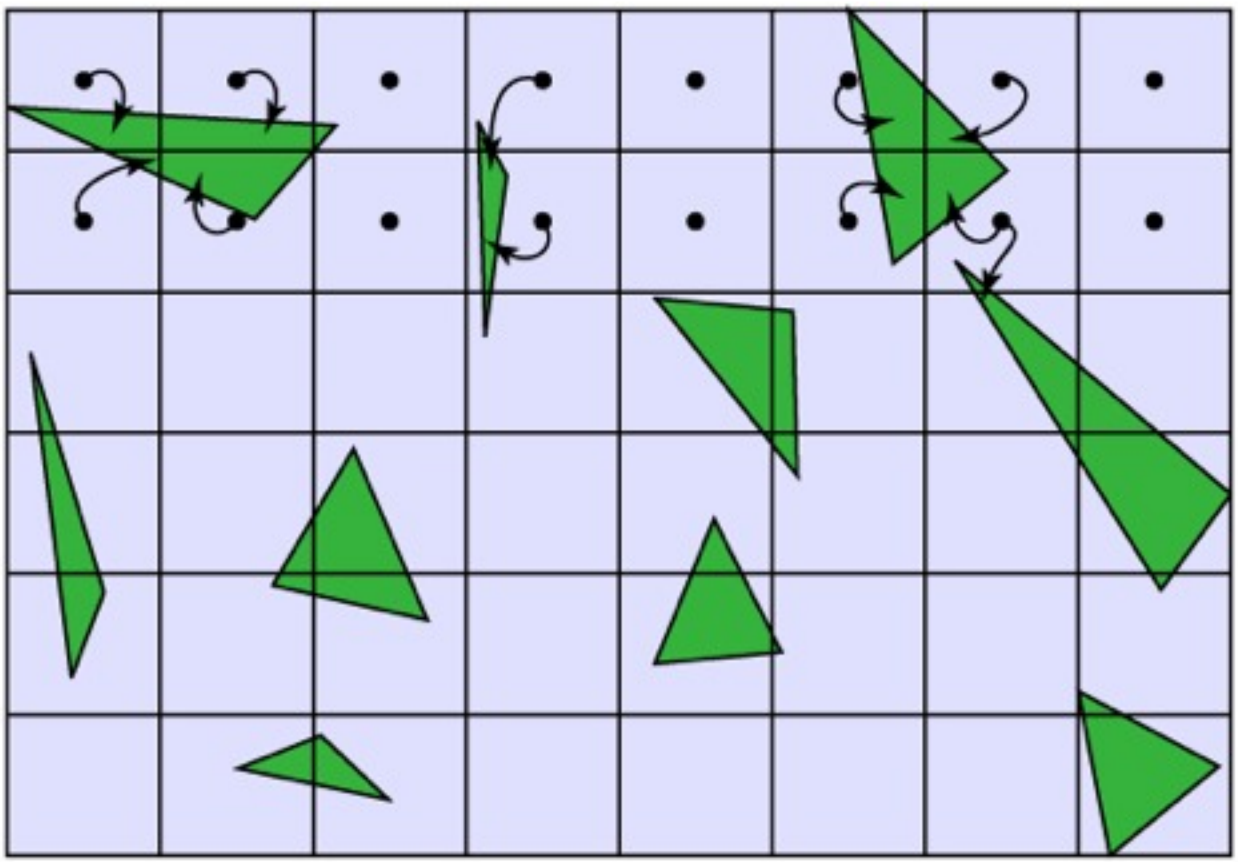
Regular space subdivision

- An entirely different approach: uniform grid of cells

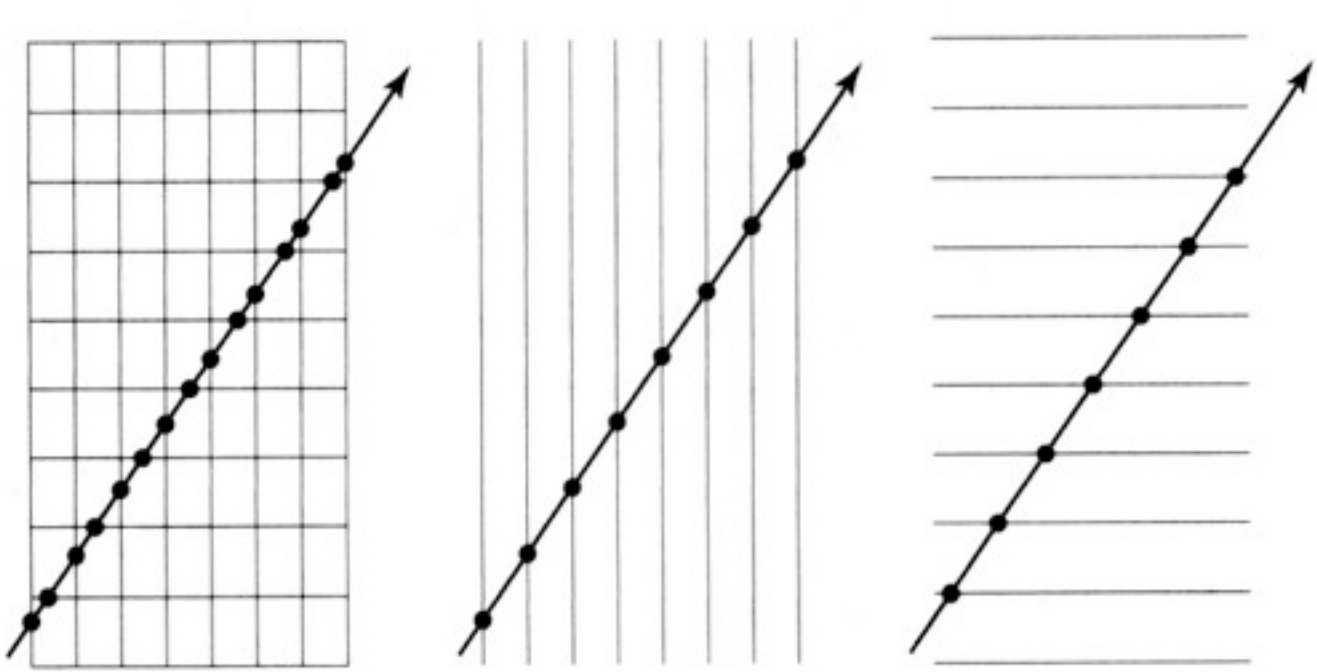


Regular grid example

- Grid divides space, not objects

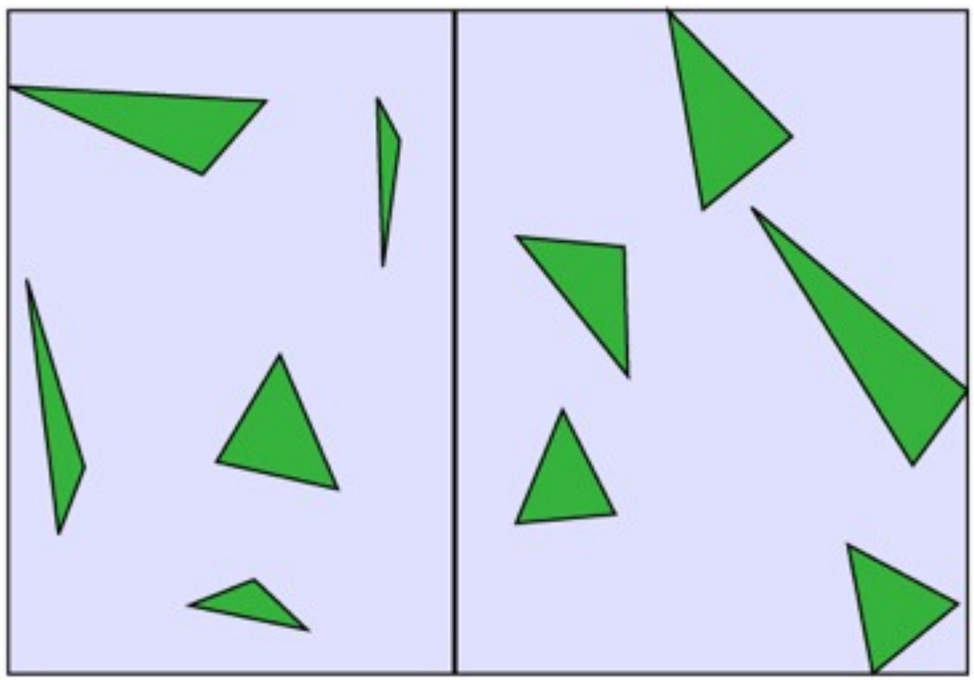


Traversing a regular grid



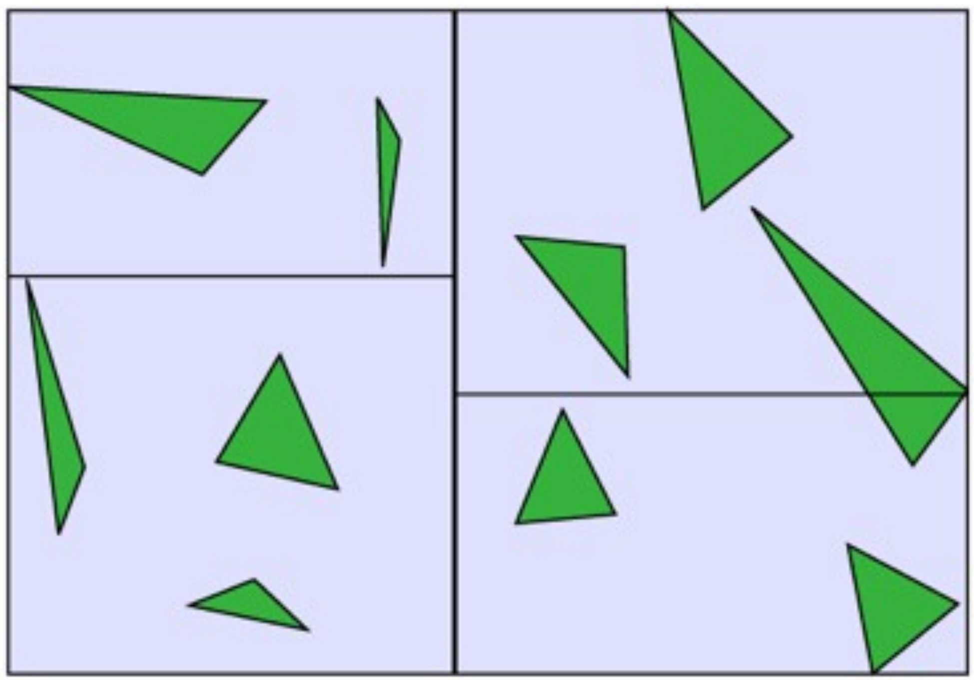
Non-regular space subdivision

- *k*-d Tree
  - subdivides space, like grid
  - adaptive, like BVH



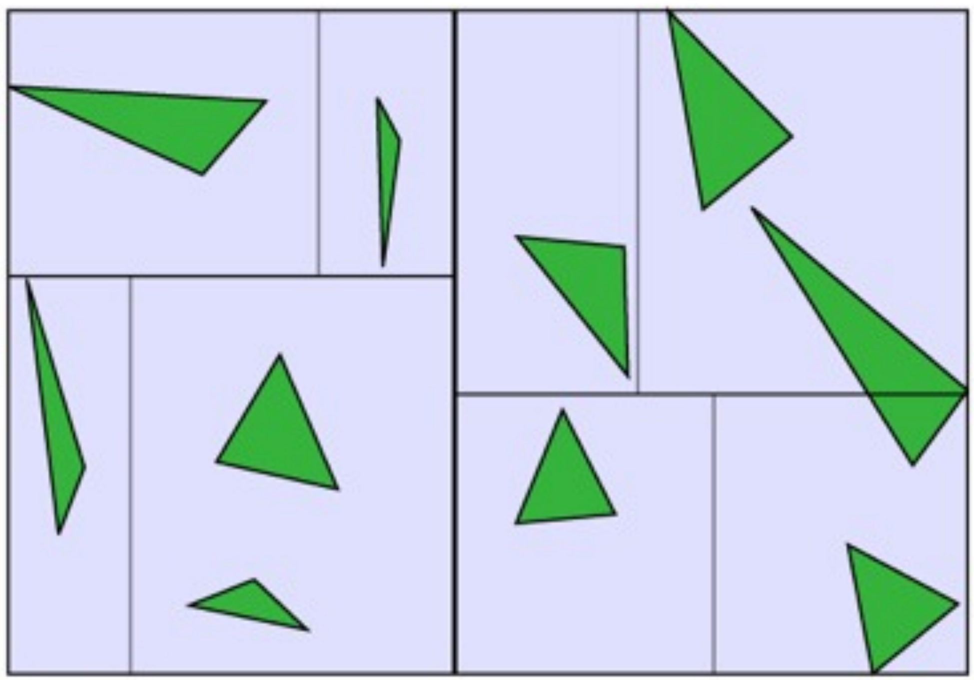
Non-regular space subdivision

- *k*-d Tree
  - subdivides space, like grid
  - adaptive, like BVH



Non-regular space subdivision

- *k*-d Tree
  - subdivides space, like grid
  - adaptive, like BVH



Implementing acceleration structures

- Conceptually simple to build acceleration structure into scene structure
- Better engineering decision to separate them

